Cosmic Evolution and Galaxy Formation: Structure, Interactions, and Feedback
ASP Conference Series, Vol. 3×10^8*, 2000*
J. Franco, E. Terlevich, O. López-Cruz and I, Aretxaga, eds.

The role of outflows and star formation efficiency in the evolution of early-type cluster galaxies

Ignacio Ferreras & Joseph Silk

Nuclear & Astrophysics Laboratory, Keble Road, Oxford OX1 3RH, U.K.

Abstract. A phenomenological model for chemical enrichment in early-type galaxies is presented, in which the process of star formation is reduced to a set of four parameters: star formation efficiency ($C_{\rm eff}$), fraction of ejected gas in outflows ($B_{\rm out}$), formation redshift (z_F) and infall timescale (τ_f). Out of these four parameters, only variations of $B_{\rm out}$ or $C_{\rm eff}$ can account for the color-magnitude relation. A range of outflows results in a metallicity sequence, whereas a range of star formation efficiencies will yield a mixed age + metallicity sequence. The age-metallicity degeneracy complicates the issue of determining which mechanism contributes the most (i.e. outflows versus efficiency). However, the determination of the slope of the correlation between mass-to-light ratio and mass in clusters at moderate or high redshift will allow us to disentangle age and metallicity.

1. Introduction

One of the long-standing problems in astrophysics is the process of star formation in galaxies. The standard scenario assumes stars to form from gas that falls in the potential wells of dark matter halos. Subsequent interacting or merging stages among galaxies might trigger additional bursts of star formation. The complex nature of star formation makes this problem rather an untractable one from an analytical point of view, so that the best approach towards understanding the distribution of stellar populations in galaxies requires a heavy use of rough approximations and all-too-often dangerous generalizations. It is the purpose of current phenomenological models describing the formation and evolution of the stellar component in galaxies to reveal the mechanisms which describe the wide range of galaxy colors and luminosities as well as their connection to morphology. The current status of the determination of the ages of the stellar populations in galaxies is rather controversial due to the degeneracy between age and metallicity (Worthey 1994). Observations of early-type galaxies by two different groups using similar techniques targeting narrow spectral indices to infer a luminosity-weighted age give contradictory results. While Trager et al. (2000) find a large age spread in the sample of field and group early-type systems of González (1993), Kuntschner (2000) reports a large metallicity spread in Fornax cluster ellipticals. So far, any observational measurement of age is plagued by many degeneracies which render a direct estimate uncertain. An alternative approach

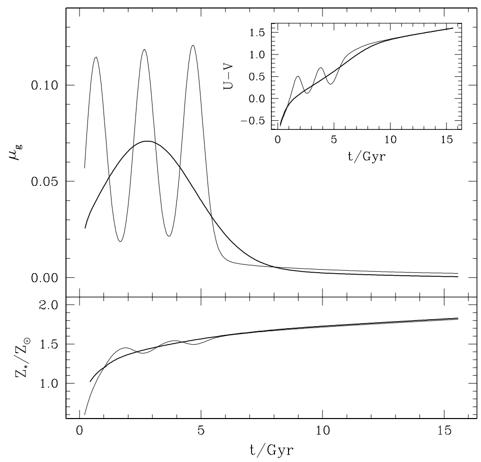

Figure 1. Gas (*top*) and metallicity (*bottom*) evolution of two models: one with a series of short bursts (*thin line*) and another with a single, more extended burst. The inset shows the evolution of $U - V$ color in the rest frame.

modelling the formation and chemical enrichment of the stellar component of galaxies is needed in order to reveal the actual scenario of galaxy formation.

2. Modelling chemical enrichment

The model presented here describes the process of star formation in early-type galaxies in terms of four parameters: star formation efficiency ($C_{\rm eff}$), ejected gas fraction in outflows ($B_{\rm out}$), formation redshift (z_F) and infall timescale (τ_f). The latter two parameters refer to the epoch ($t = t(z_F)$) at maximum and spread of a Gaussian profile for the infalling gas, i.e.:

$$f(t) \propto e^{-(t-t(z_F))^2/2\tau_f^2} \quad (1)$$

This gas will be turned into stars according to a linear Schmidt-type law, where the proportionality constant is the star formation efficiency parameter. The model is described in more detail in Ferreras & Silk (2000a,b). This generic description allows us to include multi-burst scenarios in galaxies undergoing several merging stages with enough gas to fuel star formation at each merging event. Figure 1 shows a comparison between two star formation histories: one with three equally strong starburst events and a second one as a simplification to the former using our approach. The top panel shows the evolution of the gas mass — which is proportional to the star formation rate. The bottom panel shows the evolution of the metallicity and the top inset traces the evolution of rest frame $U - V$ color for both scenarios. One can see that at times after the last bursting episode, the evolution in both cases is roughly undistinguishable. Hence, we conclude that our four-parameter model can account not only for a standard "monolithic" scenario but also for multi-burst formation histories. Furthermore,

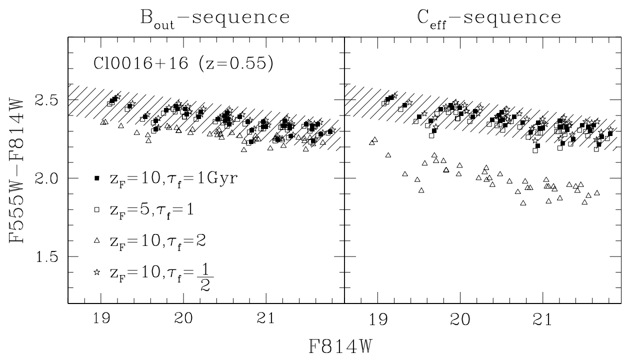

Figure 2. Evolution of the color-magnitude relation observed in Coma (Bower, Lucey & Ellis (1992) projected to moderate redshift using both an outflow-driven sequence (B_{out}, *left*) and an efficiency-driven sequence (C_{eff}, *right*). The shaded area corresponds to the observations of cluster Cl0016+16 ($z = 0.55$, Ellis et al. 1997).

a Gaussian profile for infall avoids the overproduction of low metallicity stars. In fact, a suitable choice of infall parameters (τ_f,z_F) can reproduce the local metallicity distribution of stars (Rocha-Pinto & Maciel 1996).

For a given set of four parameters ($B_{\rm out}$,$C_{\rm eff}$,z_F,τ_f) we can trace a star formation history and convolve it in age and metallicity with the simple stellar populations of Bruzual & Charlot (in preparation). Hereafter a closed cosmology ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 60$ km s^{-1} Mpc^{-1}), and a hybrid Initial Mass Function between Scalo and Salpeter (Ferreras & Silk 2000b) are used. Out of these four parameters, we find only $B_{\rm out}$ and $C_{\rm eff}$ can generate the range of observed $U - V$ colors in nearby early-type cluster galaxies (Bower, Lucey & Ellis 1992). Hence, the luminosity sequence of these systems could be explained either by a range of outflows ($B_{\rm out}$-sequence), by a range of star formation efficiencies ($C_{\rm eff}$-sequence), or by some combination thereof. Figure 2 shows the predicted color-magnitude relation (CMR) of Coma galaxies at the redshift of cluster Cl0016+16 ($z = 0.55$, Ellis et al. 1997) assuming a $B_{\rm out}$-sequence (*left*) or a $C_{\rm eff}$-sequence (*right*), and a range of infall parameters (z_F,τ_f). A sequence driven by $C_{\rm eff}$ results in an age spread for the stellar populations. This causes the remarkable departure of the predictions from the observed CMR (shaded area) for extended star formation histories ($z_F = 10$, $\tau_f = 2$ Gyr). However, because of the age-metallicity degeneracy, we find that quite a large range of the parameters agree with the observations within error bars. Hence, we cannot use photometric measurements of moderate redshift clusters in order to determine whether age ($C_{\rm eff}$) or metallicity ($B_{\rm out}$) drive the CMR.

3. M/L ratio as tracer of age evolution

One of the most age-sensitive observables is the mass-to-light ratio. Hence, the predicted evolution of M/L with lookback time should be different for sequences driven by age or by metallicity. We consider the evolution with redshift of the slope of the correlation between M/L in rest frame B-band and *stellar* mass. This slope change is parametrized by η_B defined as follows:

$$\eta_B(z) \equiv \frac{\Delta \log M/L_B}{\Delta \log M}\Big|_z - \frac{\Delta \log M/L_B}{\Delta \log M}\Big|_{z=0} \tag{2}$$

For a $B_{\rm out}$-sequence (driven by outflows), the range of luminosities is related by a spread in metallicities. As we evolve the cluster to higher redshifts, the mass-to-light ratio will decrease uniformly across the luminosity sequence because of lookback time, and there will also be a relative change of M/L among early-type galaxies caused by its very weak metallicity dependence, which makes the decrease in mass-to-light ratio slighly larger in galaxies with a higher metallicity, thereby flattening the slope of M/L vs M (i.e. $\eta_B \lesssim 0$). On the other hand, a $C_{\rm eff}$-sequence (driven by efficiency) will introduce a significant age spread which varies with galaxy mass, so that M/L at the fainter end (which has a lower efficiency and thus a larger age spread) will decrease more than the bright end, steepening the slope (i.e. $\eta_B > 0$, see figure 5 in Ferreras & Silk 2000b).

This behavior makes the study of the evolution of M/L with redshift a suitable candidate to infer the star formation history of early-type cluster galaxies. Unfortunately, this observable still poses a long string of uncertainties which prevent it from establishing a clearcut way of breaking the degeneracy between age and metallicity: mass-to-light ratios require time-consuming spectral observations in order to measure velocity dispersions, and can only be achieved with 10m class telescopes for clusters at moderate and high redshifts. Furthermore, the measured M/L ratios (inferred from observations of velocity dispersions, surface brightnesses and galaxy sizes) rely on a set of assumptions about the structure of the galaxy. Any correlation between galaxy structure and mass or luminosity will add systematic errors which are hard to estimate. However, alternative age-dependent observables such as Balmer spectral indices are also plagued by model-dependent uncertainties. Despite all these caveats, the study of the evolution of M/L with lookback time is still one of the best methods to determine the stellar demography in galaxies.

References

Bower, R. G., Lucey, J. R. & Ellis, R. S. 1992, MNRAS, 254, 601

Ferreras, I. & Silk, J. 2000a, ApJ, March 20, astro-ph/9910385

Ferreras, I. & Silk, J. 2000b, MNRAS, in press

González, J. J. 1993, Ph.D. thesis, University of California

Kuntschner, H. 2000, MNRAS, in press (astro-ph/0001210)

Rocha-Pinto, H. J. & Maciel, W. J. 1996, MNRAS, 279, 447

Trager, S. C., et al. 2000, AJ, in press (astro-ph/0001072)

Van Dokkum, P. G., et al. 1998, ApJ, 504, L17

Worthey, G. 1994, ApJS, 95, 107